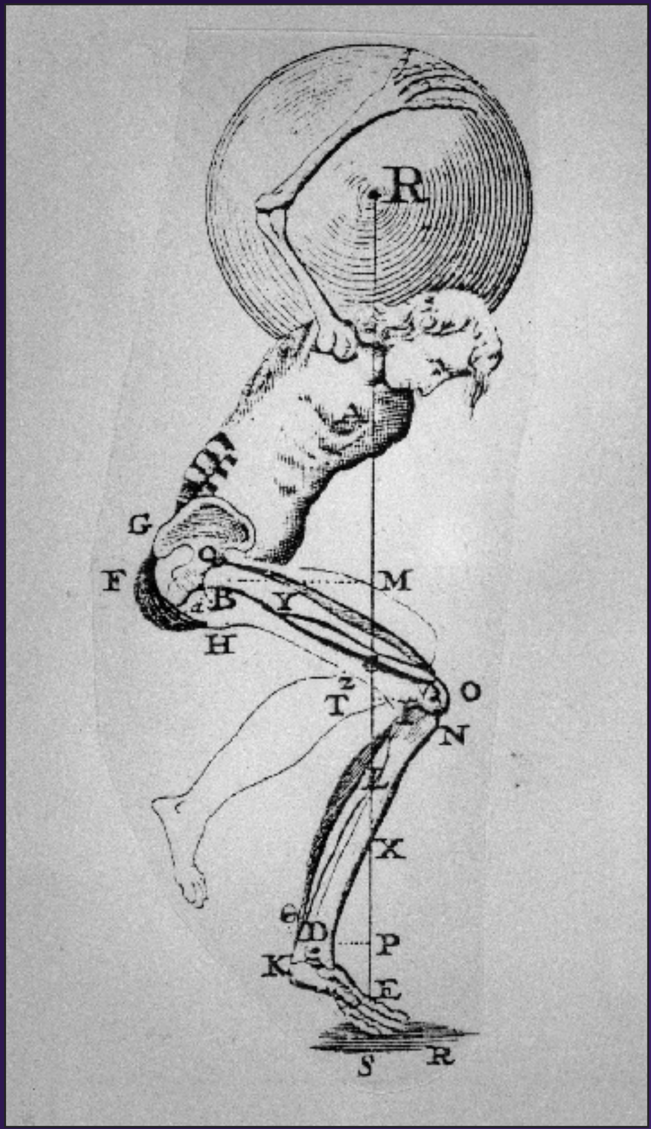


Musculoskeletal Biomechanics

BIOEN 520 | ME 527

Session 7A

Computational Modeling

Review: Session 5A, 5B and 6

- Imaging in Biomechanics
  - The Matrix
  - The Beatles
- Biochemistry and histology
  - Constituents
  - Structure
    - Removing bias
  - Don't mouth pipet
- Tour and lab at ABL
- Homework #1

Session 7 Overview...

- Review sessions 5A, 5B, and 6
- Class modeling experiences
- Define model and simulation
- Motivation - why develop models?
- Types of models
- Important modeling considerations
- Specific modeling examples

Class modeling experiences

- PhD student with thesis topic
- PhD student
- MS student with thesis topic
- MS student
- Undergraduate research
- Computational modeling class
- Imagine a mass sitting on a spring

Model vs. Simulation

- Model

  an attempt to represent reality

- Simulation (or computer simulation)

  experimentation using a model

Nigg 1998

Computational modeling/simulation

- Computer modeling:

  refers to the setting up of mathematical equations to describe the system of interest, the gathering of appropriate input data, and the incorporation of these equations and data into a computer program.

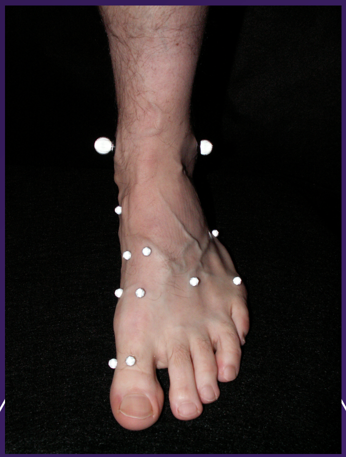
- Computer simulation:

  is restricted to mean the use of a validated computer model to carry out experiments, under carefully controlled conditions, on the real-world system that has been modeled.

  Vaughn 2002

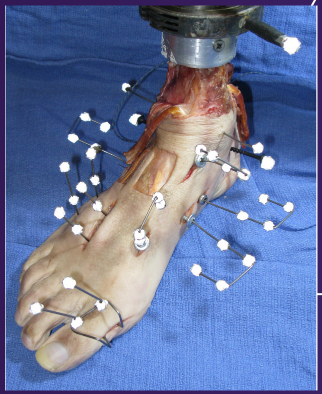
Motivation - why develop models?

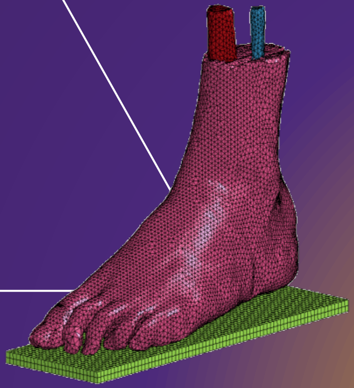
There are three ways to study part of the body: living subjects, cadavers, and computation models. Each has its own place and role.



Perhaps a future role for anatomically correct test beds?

Foot





Why develop models?

- Addresses various issues with living subjects and/or cadavers:

    expensive

    availability (age, vascular state)

    unethical

    some things cannot be measured directly

    some things cannot be measured safely

    cannot be reset - "one and done"

    cannot conduct parametric analyses

    absolute repeatability

    time required

Why develop models?

- Model complexity

  what level of detail do you need?

- Harvard tuned track

  http://tinyurl.com/kzyyydm

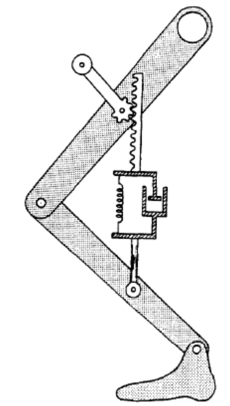
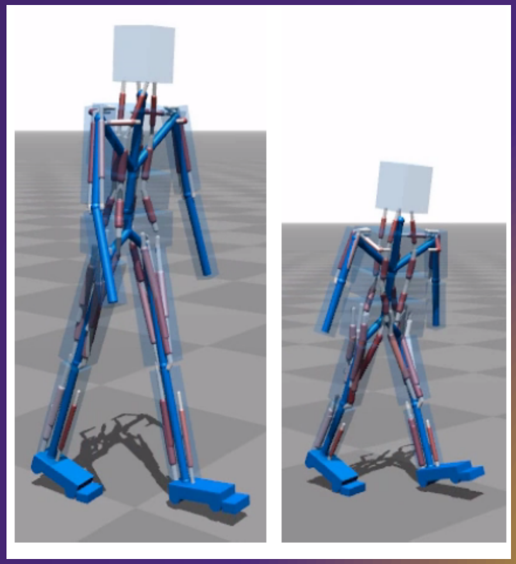


Fig. 1. Schematic representing the separate role of descending commands (rack-and-pinion) and muscle properties plus local reflexes (damped spring). The motion of the rack and pinion element determines the influence of track stiffness on step length. The runner's mass and the damped spring determine the influence of track stiffness on ground contact time.

- Flexible Muscle-Based Locomotion for Bipedal Creatures

  http://vimeo.com/79098420



Why develop models?

- Limitations:
  - validation difficult, but necessary
  - very time consuming to get it right
  - complex (advanced mathematics, numerous parameters, simulation times, etc.)
  - difficult to transfer results to real world (i.e., what do results really mean?)

Types of models

- analytical vs. numerical or computational
- black box/phenomenological vs. physiologic
- continuous vs. discrete (lumped parameter)
- forward vs. inverse

Important modeling considerations

- purpose/question/motivation
- previous research
- level of complexity/assumptions
- geometry/anatomy/morphometry
- material properties
- boundary conditions
- validation
- simulation/results
- limitations/interpretation/future work

Specific modeling examples

- lumped parameter (tuning track)
- inverse dynamic (gait analysis)
- musculoskeletal (SIMM, OpenSIM, Anybody)
- forward dynamic (simulation of walking)
- finite element modeling

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Lumped Parameter Models

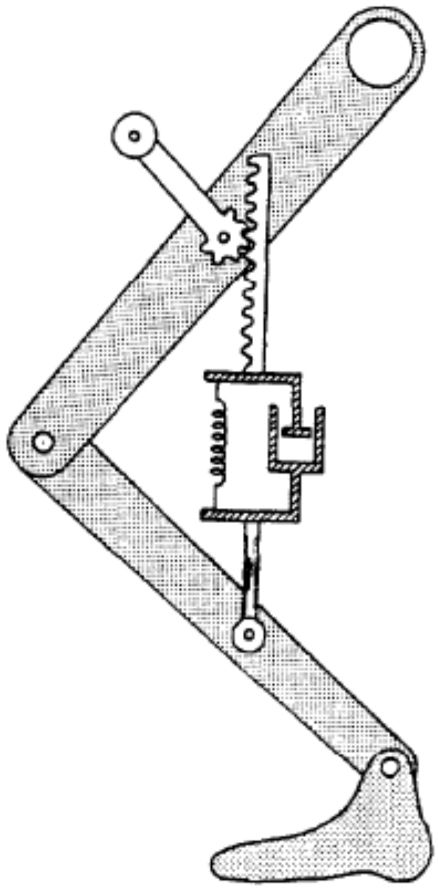


Fig. 1. Schematic representing the separate role of descending commands (rack-and-pinion) and muscle properties plus local reflexes (damped spring). The motion of the rack and pinion element determines the influence of track stiffness on step length. The runner's mass and the damped spring determine the influence of track stiffness on ground contact time.

Lumped Parameter Models

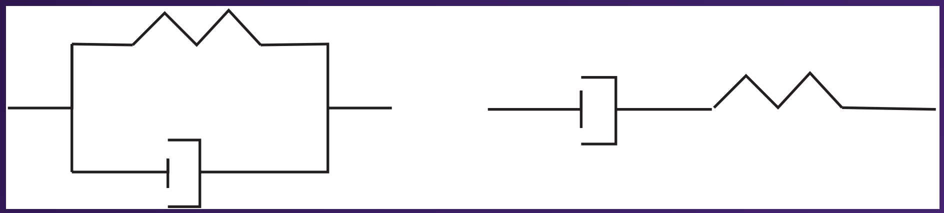
- define a system with a finite number of state variables
- able to describe system behavior with ODE instead of PDE

Lumped Parameter Models

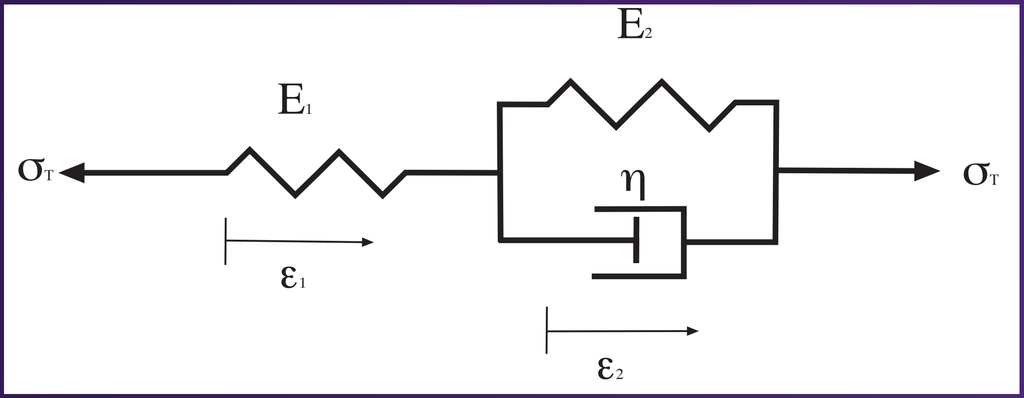
- basic types of elements
  - spring
  - dashpot
  - mass
- linear, rotational
- friction, inertial

Lumped Parameter Models

- Kelvin-Voigt
- Maxwell

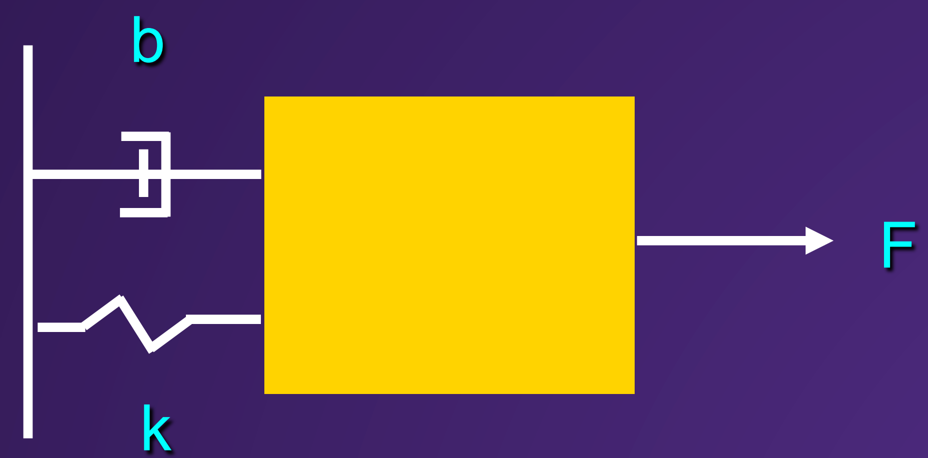


- Standard linear solid



Lumped Parameter Models

- Second order systems



Lumped Parameter Models

- Second order systems

$$m\ddot{x} + b\dot{x} + kx = F$$

Lumped Parameter Models

- Second order systems - free vibration

$$m\ddot{x} + b\dot{x} + kx = 0$$

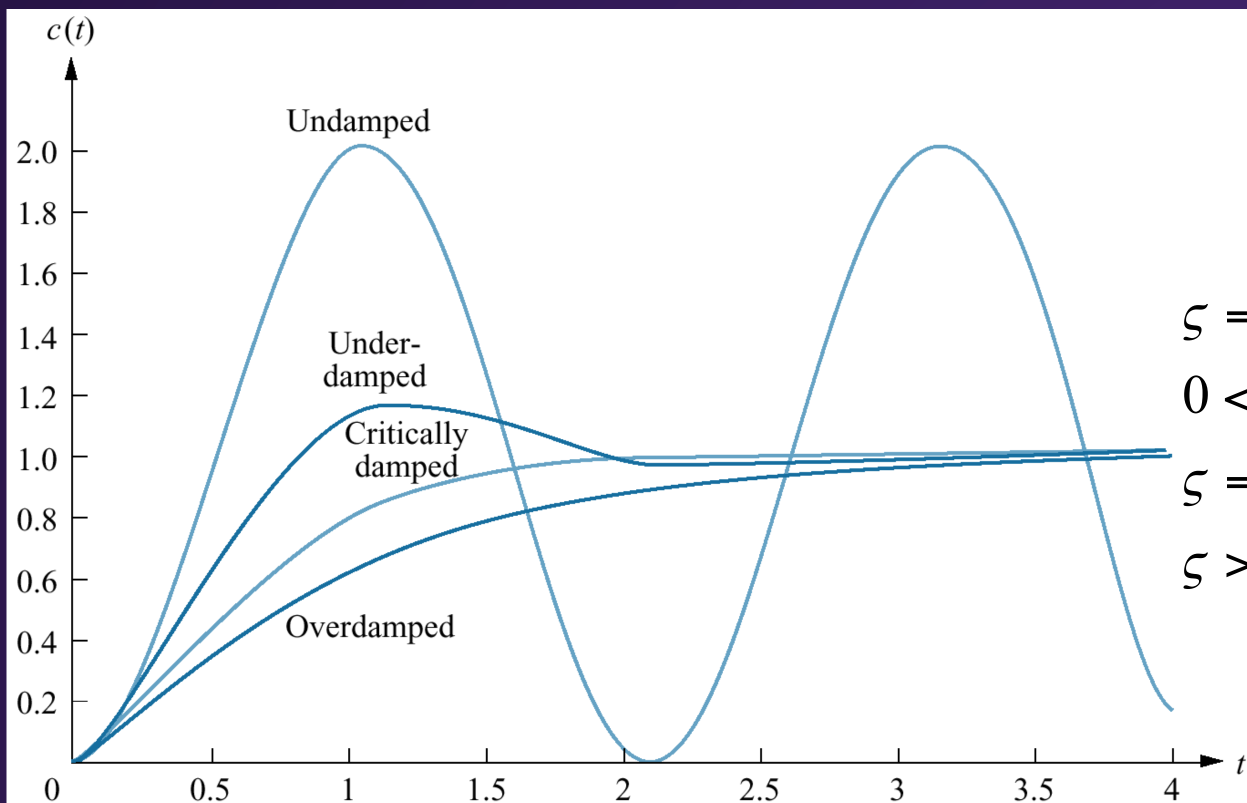
$$\ddot{x}(t) + 2\zeta\omega\dot{x}(t) + \omega^2 x(t) = 0$$

$$\omega = \sqrt{k/m}$$

$$\zeta = b/2m\omega$$

Lumped Parameter Models

Step Response of Second-Order System with Various Damping Ratios



$\varsigma = 0 \Rightarrow \textit{Undamped}$

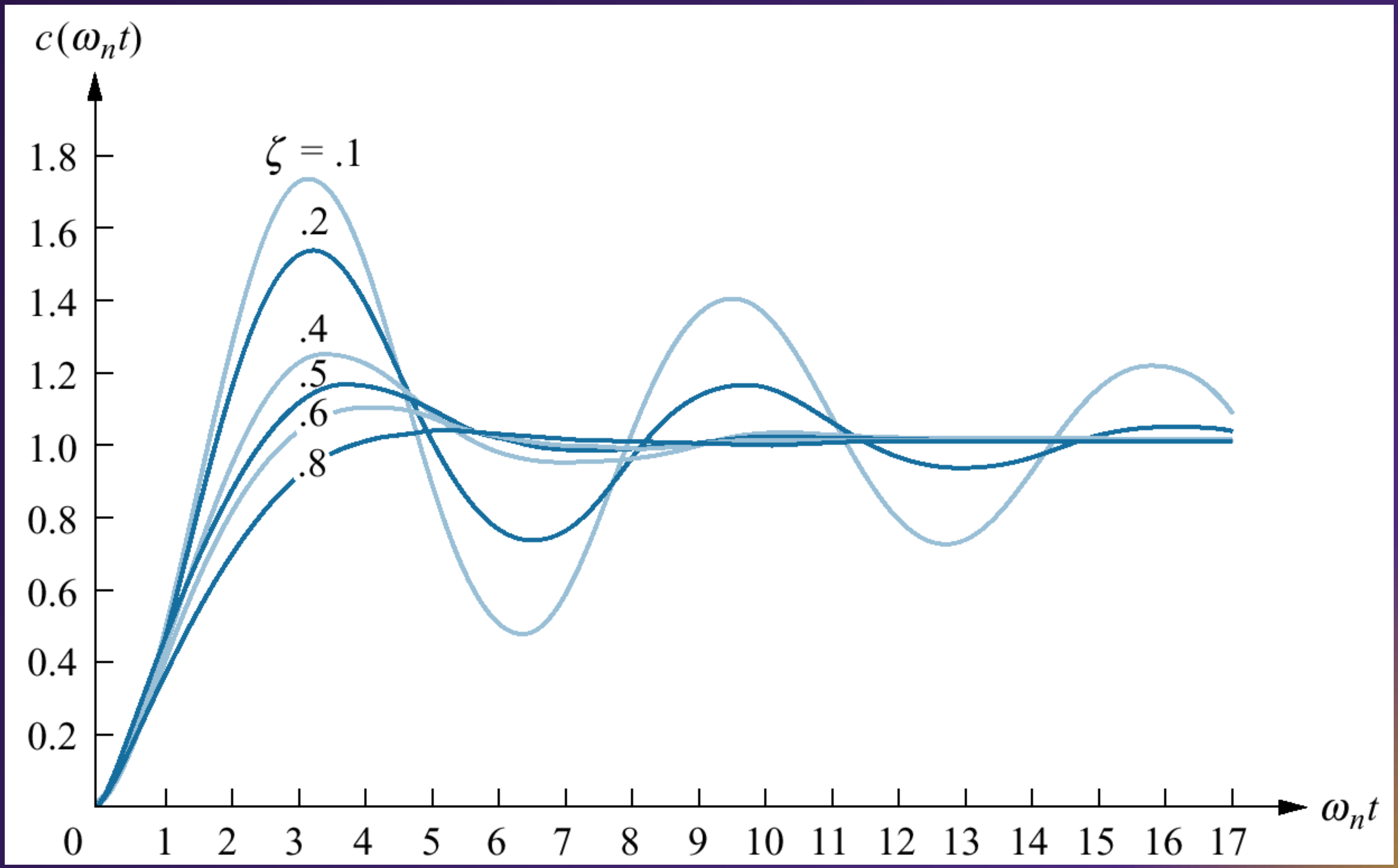
$0 < \varsigma < 1 \Rightarrow \textit{Underdamped}$

$\varsigma = 1 \Rightarrow \textit{Critically damped}$

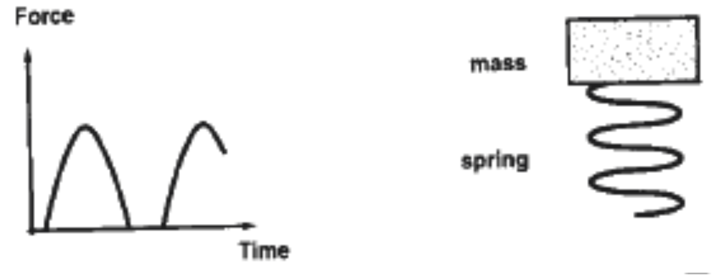
$\varsigma > 1 \Rightarrow \textit{Overdamped}$

Lumped Parameter Models

Step Response for Various Damping Ratios

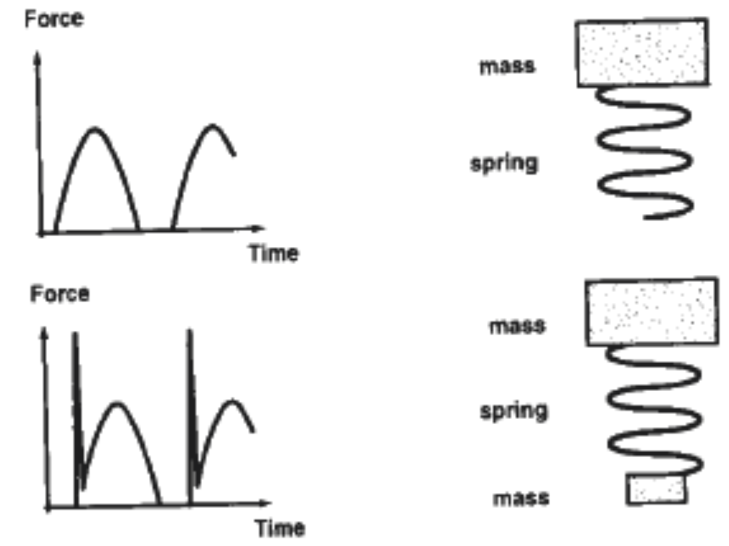


Lumped Parameter Models



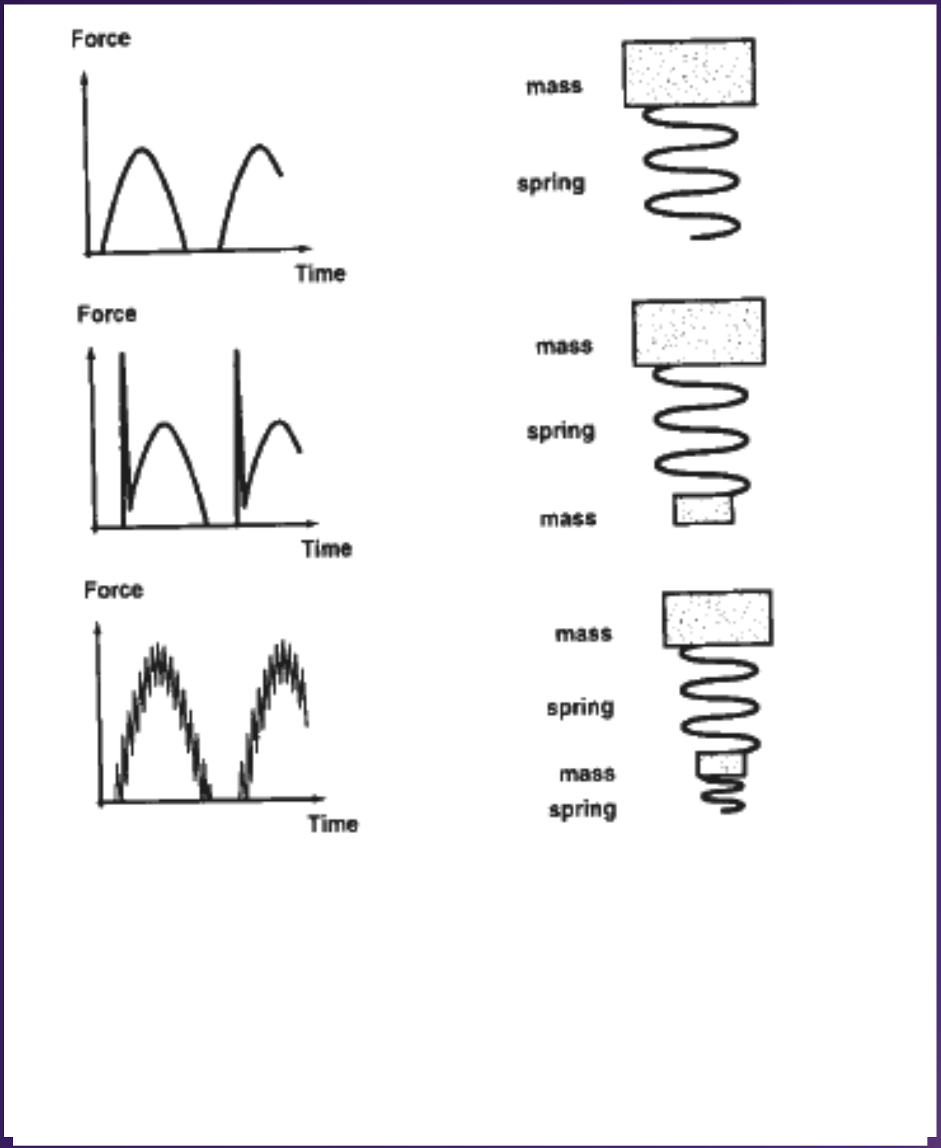
Nigg 1998

Lumped Parameter Models



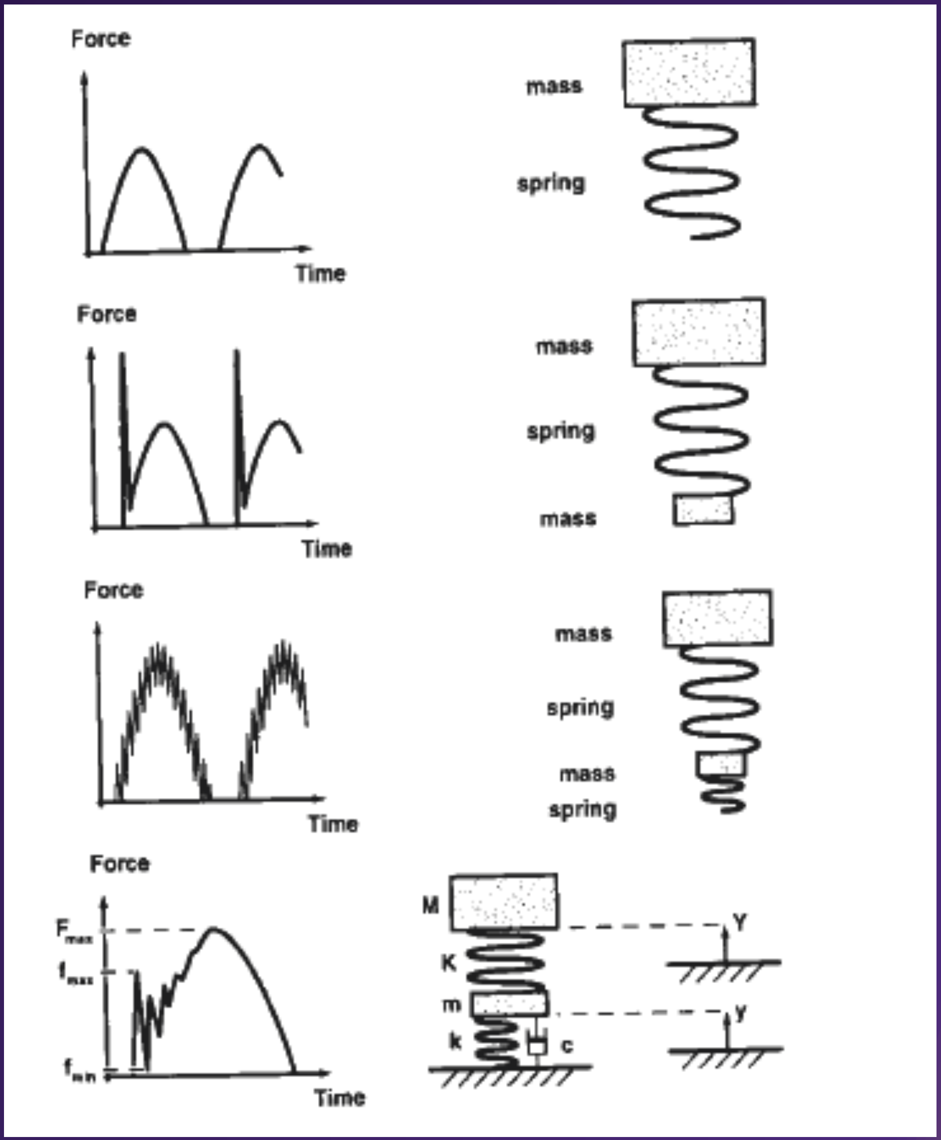
Nigg 1998

Lumped Parameter Models



Nigg 1998

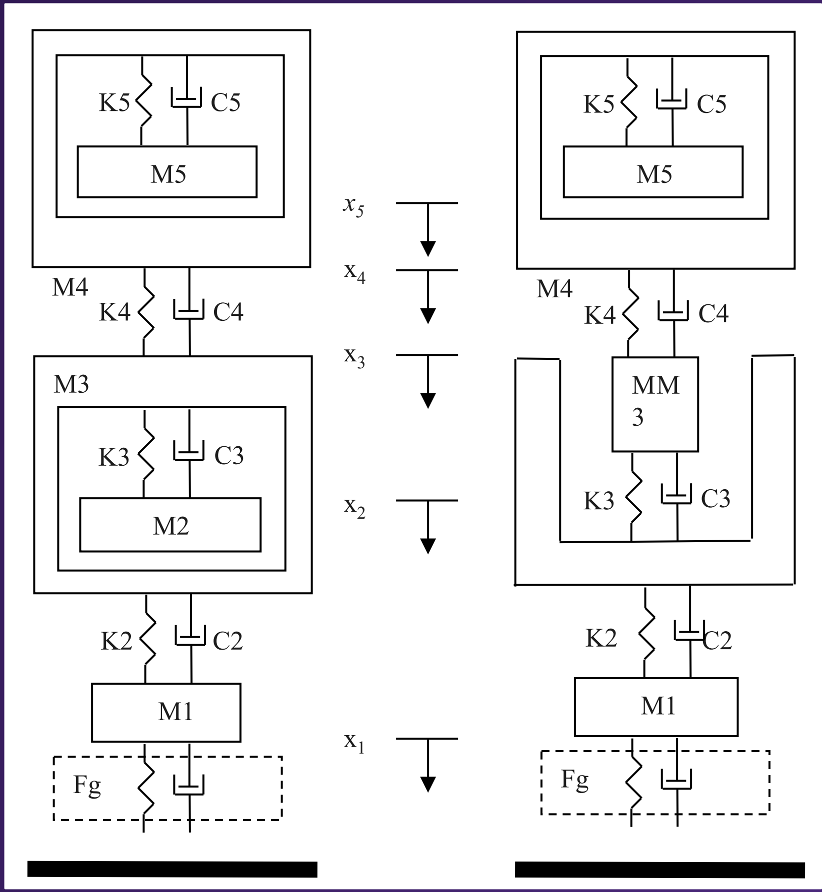
Lumped Parameter Models



Nigg 1998

Lumped Parameter Models

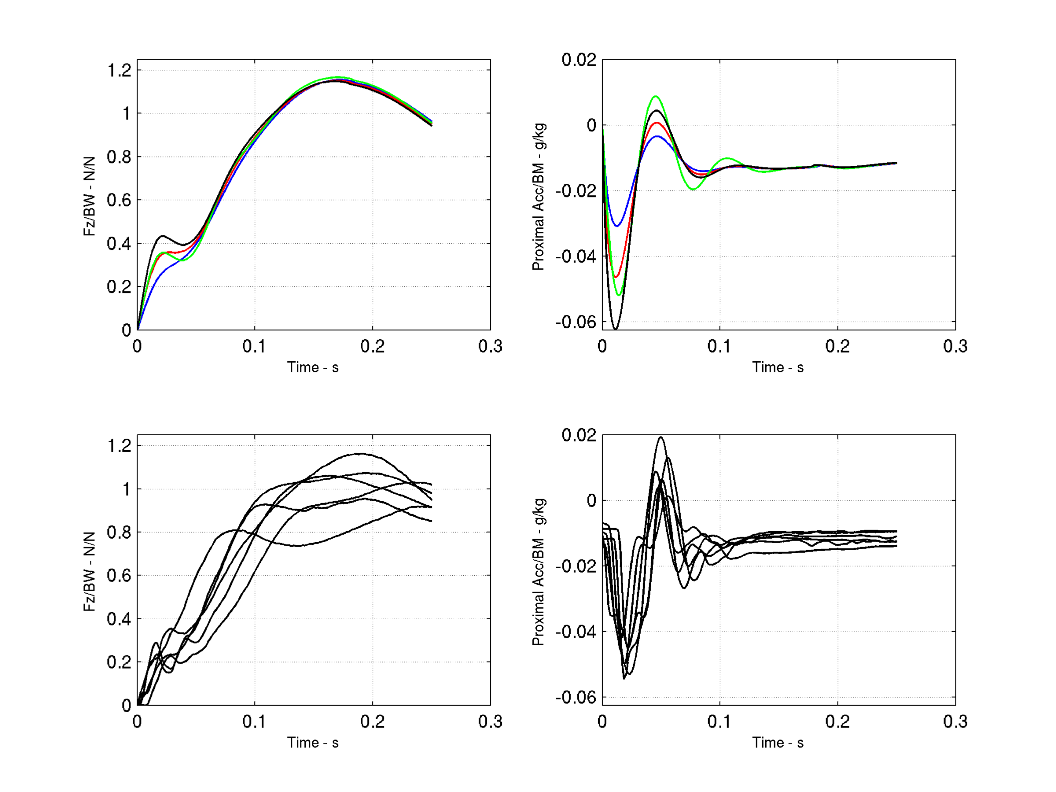
- Intact limb vs. transtibial amputee



Klute 2004

Lumped Parameter Models

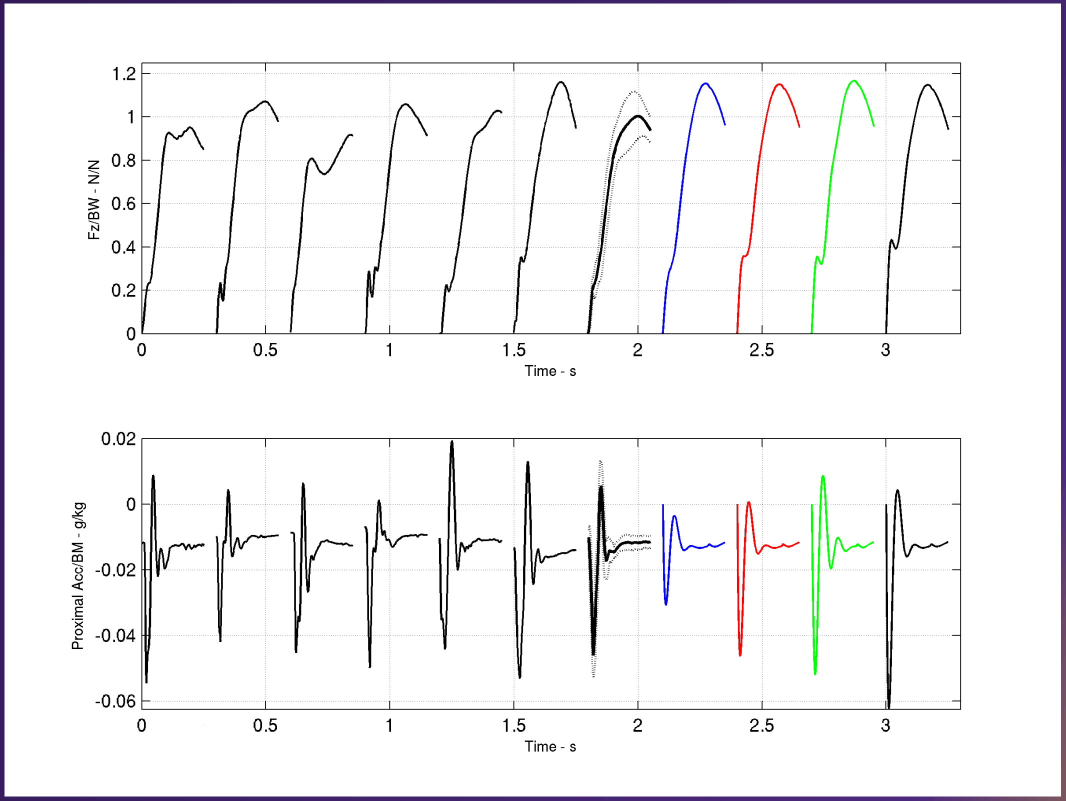
- Intact limb vs. transtibial amputee
  - Top – 4 model plots
  - Bottom – 6 amputee gait trials



Klute 2004

Lumped Parameter Models

- Intact limb vs. transtibial amputee
  - First 6 trials – amputee gait; 7th is average data
  - Last 4 trials – adjust model to individual behavior



Klute 2004

Specific modeling examples

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- inverse dynamic (gait analysis)
- musculoskeletal (SIMM, OpenSim, Anybody)
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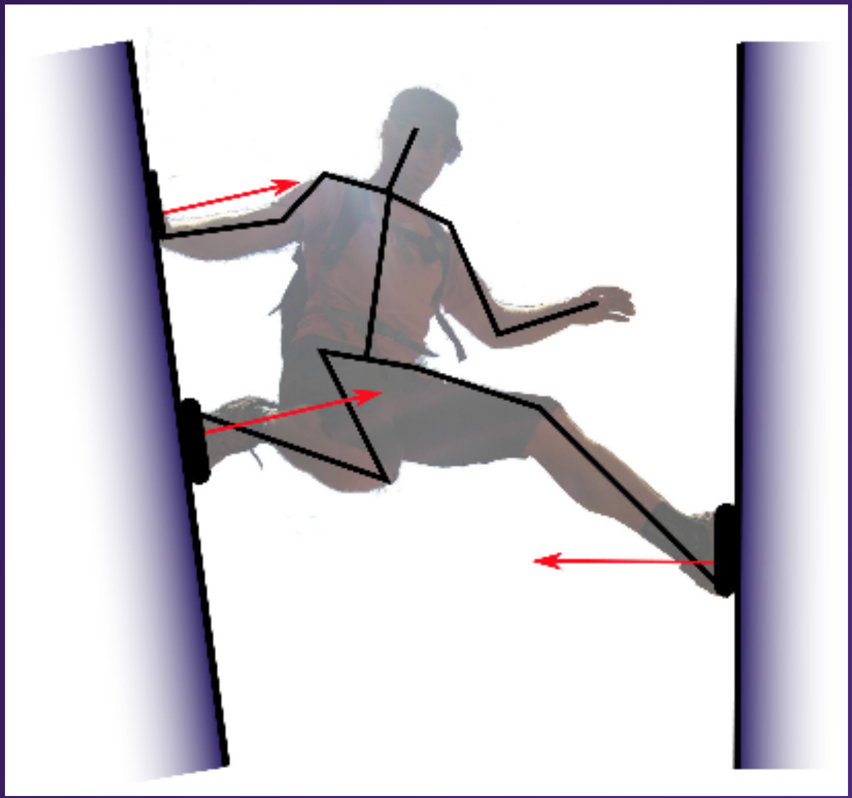
- finite element modeling

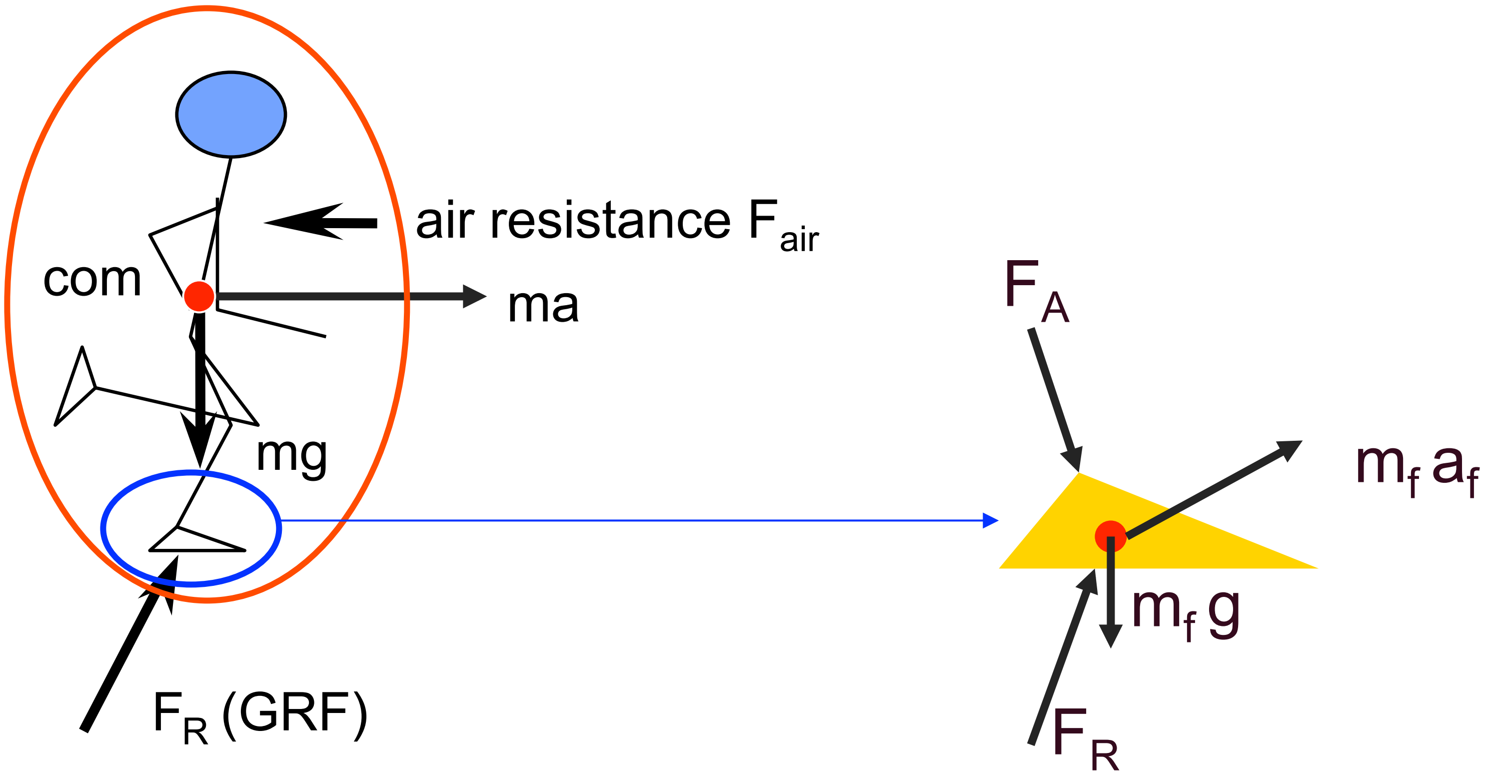
Inverse dynamic (gait analysis)

- Estimate joint forces and torques from rigid body kinematics, external forces, and inertial forces.
- Not only in laboratory now.



Inverse dynamic (gait analysis)

- Most common example



$\sum F = F_R + mg + F_{air} = ma$

$\sum F = F_R + m_f g + F_A = m_f a_f$

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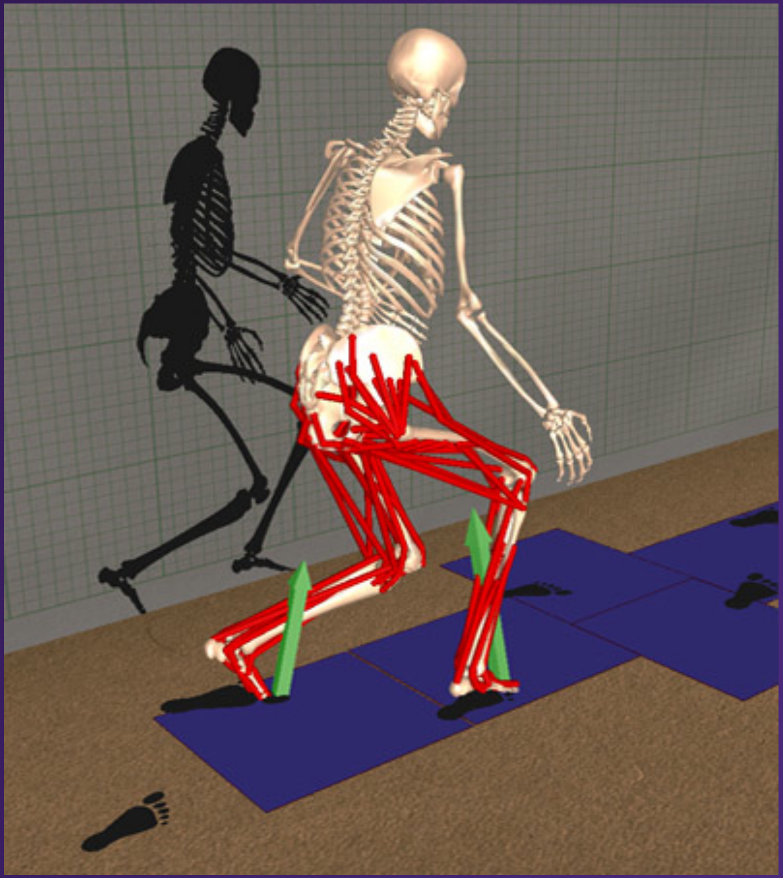
Musculoskeletal models

- Tool kits that allow for modeling, animation, and analysis of 3D musculoskeletal systems.
- Includes representations of joints, bones, muscles, ligaments, and other structures.
- Calculate the joint moments that each muscle can generate at any body positions.
- Can also be used for forward or inverse dynamic analyses.
- Used to model walking, cycling, running, jumping, weight lifting, reaching, and throwing.

Musculoskeletal

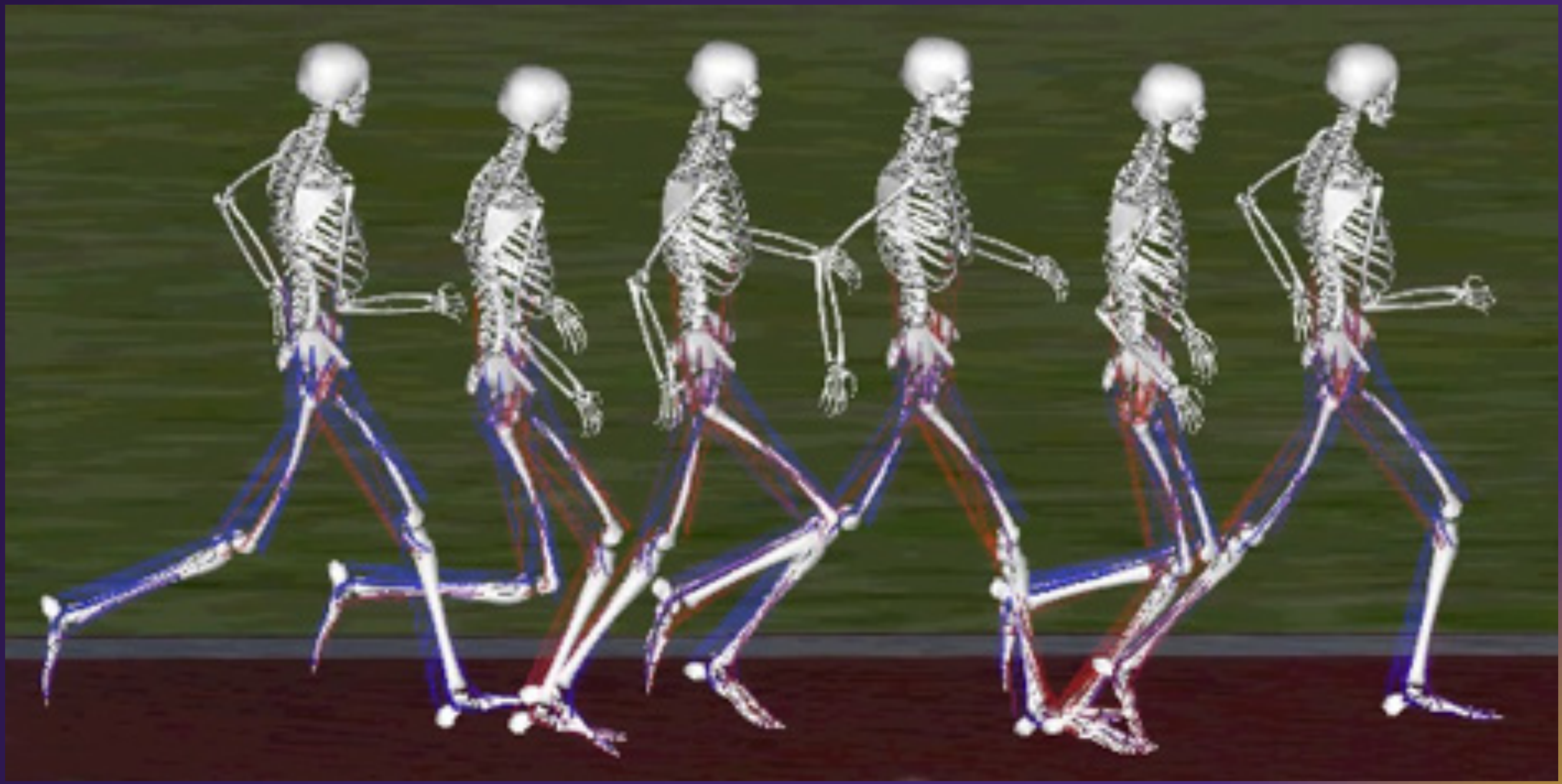
- SIMM – software for interactive musculoskeletal modeling



http://www.musculographics.com

Musculoskeletal

- OpenSim



https://simtk.org/home/opensim and http://opensim.stanford.edu

Musculoskeletal

- Anybody

http://www.anybodytech.com

Specific modeling examples

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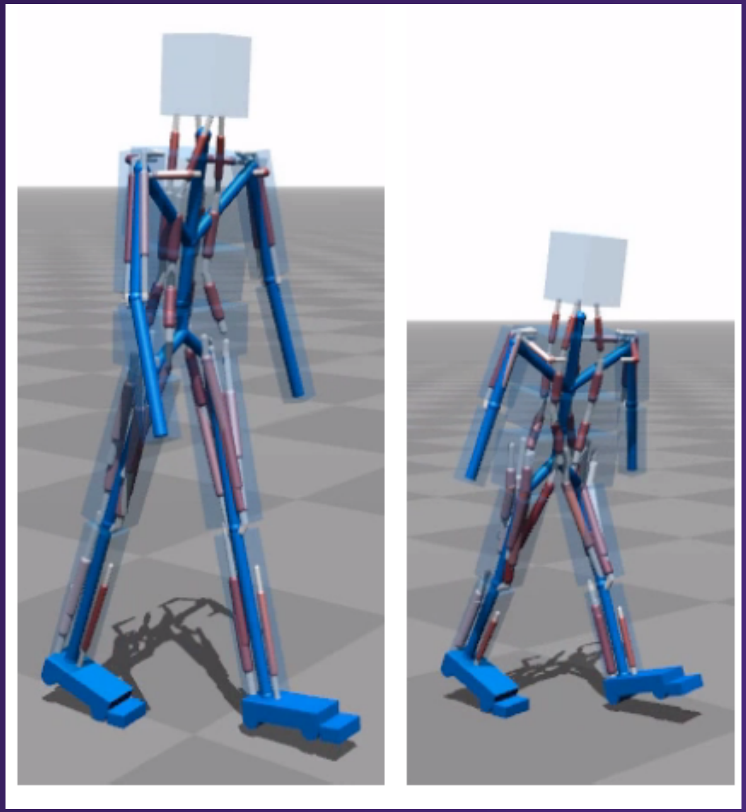
Forward dynamic

- Estimate limb kinematics from joint forces and torques, or even individual muscle forces.
- Flexible Muscle-based Locomotion



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Finite element modeling

- Computerized method for predicting response of an object to real world forces, vibrations, heat, fluid flow, etc.
- Break down a real object into a large number (1,000s to 100,000s) of very small little cubes (finite elements).
- Mathematical equations to predict behavior of each element.

Finite element modeling

- Computational foot modeling